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Supersymmetric Dark Matter and the Energy of a Linear Electron-Positron Collider

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Abstract

We suggest that supersymmetric dark matter be used to set the energy scale of a linear e^+e^- collider. Assuming that the lightest supersymmetric particle (LSP) is a stable neutralino χ, as in many incarnations of the MSSM with conserved R parity, previous calculations that include coannihilation effects have delineated the region of the $(m_{1/2}, m_0)$ plane where the LSP cosmological relic density lies in the preferred range $0.1 \lesssim \Omega_\chi h^2 \lesssim 0.3$. We evaluate here the total cross section for $e^+e^- \to$ visible pairs of supersymmetric particles, for different values of $m_{1/2}$ and m_0, and investigate how much of the dark matter region can be explored by e^+e^- colliders with different centre-of-mass energies E_{CM}. We find that a collider with $E_{CM} = 500$ GeV or 1 TeV can only explore part of the cosmological region, and that a collider with $E_{CM} = 1.5$ TeV with sufficient luminosity can explore all of the supersymmetric dark matter region.

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1 Introduction

One of the most promising ideas for a high-energy accelerator to complement the LHC is a linear e^+e^- collider (LC) with a centre-of-mass energy E_{CM} in the TeV range [1]. The crucial parameters of such a LC are E_{CM} and the luminosity. The optimal choice of E_{CM} is constrained by technology and cost, but should be driven by physics arguments based on the accessibility of physics thresholds. One established threshold in the energy range of interest is that for $e^+e^- \to \bar{t}t$ at about 350 GeV [2]. A second threshold likely to be in this energy range is that for Higgs boson (H) production via the reaction $e^+e^- \to H + Z$ [3]. For some years [4], the precision electroweak data have favoured a relatively light Higgs boson, as suggested independently by supersymmetry. The most recent indication is that $M_H \lesssim 200$ GeV at the 95 % confidence level [5], corresponding to a $H + Z$ threshold below about 300 GeV.

Since supersymmetry is widely considered to be one of the most promising possible low-energy extensions of the Standard Model, it is desirable that any new collider offer good prospects of detecting at least some supersymmetric particles, as is the case of the LHC [6]. The physics argument that has usually been employed to estimate the sparticle mass scale $\tilde{m}$ has been that of the naturalness of the gauge hierarchy, which suggests that $\tilde{m} \lesssim 1$ TeV [7]. A supporting argument has been the concordance of the gauge couplings measured at LEP and elsewhere with the predictions of supersymmetric Grand Unified Theories (GUTs) [8]. However, this argument is sensitive only logarithmically to $\tilde{m}$, and is also vulnerable to GUT threshold effects due to particles beyond the minimal supersymmetric extension of the Standard Model (MSSM). The agreement of the Higgs mass range favoured by the precision electroweak data with that calculated in the MSSM [9] is also encouraging, but is again only logarithmically sensitive to $\tilde{m}$, and hence unable to specify it with any accuracy.

An independent argument for new physics around the TeV scale is provided by calculations of cold dark matter, which yield naturally a freeze-out density in the cosmologically allowed range: $\Omega_{CDM} h^2 \lesssim 0.3$ (where $\Omega \equiv \rho/\rho_c$, the critical density, and h is the Hubble expansion rate in units of 100 km/s/Mpc), and that preferred by theories of structure formation: $0.1 \lesssim \Omega_{CDM} h^2$, if the mass of the cold dark matter particle is $\lesssim 10$ TeV [10]. The upper limit on $\Omega_{CDM} h^2$ is fixed by the age of the Universe. For $\Omega_{tot} \leq 1$, a lower limit on the age of the Universe of 12 Gyr implies an upper limit $\Omega_m h^2 < 0.3$ on the total matter density, and hence $\Omega_{CDM} < \Omega_m$. This argument does not rely on the high-redshift supernova observations [11], but they do support it.

A serendipitous prediction of Ω_{CDM} is provided by the MSSM with R parity conservation [12], if the lightest supersymmetric particle (LSP) is the lightest neutralino χ, as in many versions of the MSSM. Indeed, it has been shown [13] that the most 'natural' choices of MSSM parameters, from the point of view of the gauge hierarchy, yield a relic LSP density in the astrophysical and cosmological region $0.1 \lesssim \Omega_\chi h^2 \lesssim 0.3$. In this case, detailed calculations of the relic LSP abundance yield $\Omega_{CDM} \leq 0.3$ only for $m_\chi \lesssim 600$ GeV [14]. An essential role in this relic density calculation is played by $\chi - \tilde{\ell}$ coannihilation effects when the LSP is mainly a gaugino, which increase significantly the upper limit on the LSP mass quoted previously [15].

The idea we propose in this paper is that the relic density calculation be used to specify the likelihood that a LC with given E_{CM} will be above the sparticle pair-production threshold, and able to detect at least some supersymmetric cross section. The answer is necessarily higher than $E_{CM} = 2 \times m_\chi^{max}$, since the process $e^+e^- \to \chi\chi$ is not directly observable in models with a stable neutralino LSP χ. On the other hand, as we discuss in more detail below, $m_\chi^{max} \sim 600$ GeV is attained when $m_\chi \sim m_{\tilde{\tau}}$, with $m_{\tilde{\mu}}, m_{\tilde{e}}$ not much heavier, so one might expect that a LC with E_{CM} not far above 1200 GeV should be sufficient. As we show in more detail below, a LC with $E_{CM} = 500$ GeV or 1 TeV would only be able to detect supersymmetry in a fraction of the preferred dark matter region of MSSM parameter space. A LC with $E_{CM} = 1.5$ TeV would probably cover the preferred region, but might miss some part of the $\chi - \tilde{\ell}$ coannihilation 'tail' at large $m_{1/2}$, depending on the luminosity it attains. A LC with $E_{CM} = 2$ TeV would, on the other hand, be able to cover all the cosmological region with a comfortable safety margin in terms of cross section, kinematic acceptance and astrophysical uncertainties.

2 Summary of LSP Density Calculations

We assume R parity is conserved, otherwise there would be no stable supersymmetric dark matter to interest us. We work within the constrained MSSM, in which all the supersymmetry-breaking soft scalar masses are assumed to be universal at the GUT scale with a common value m_0, and the gaugino masses are likewise assumed to be universal with common value $m_{1/2}$ at the GUT scale [16]. The constrained MSSM parameters are chosen so as to yield a consistent electroweak vacuum with a value of $\tan\beta$ that is left free. The LEP lower limits on MSSM particles, including the lightest Higgs boson, suggest that $\tan\beta \gtrsim 3$, so we consider this and the higher value $\tan\beta = 10$. We consider two possible values of the trilinear soft supersymmetry-breaking parameter: $A = 0, -m_{1/2}$, the latter being the value for which the constraint that the lowest-energy state not break charge and colour (CCB) is weakest [17], consistent with parameter choices out to the point at the tip of the cosmological region.

When calculating the relic density of LSPs χ, it is assumed that they were in thermal equilibrium prior to freeze-out at some temperature T_f. The relic density after freeze-out is then determined by the competition between the expansion rate of the Universe and the neutralino annihilation rate. Ultimately, the relic density is inversely related to the effective annihilation cross section σ_{eff}, which falls off as the square of the supersymmetry breaking scale. Thus, as the supersymmetry breaking scale is increased, the annihilation cross section decreases and the relic density increases. This is why an upper limit to the relic density puts an upper limit on the sparticle mass scale, and on the mass of the neutralino LSP, in particular. In regions where the neutralino is mainly a gaugino (usually a bino), as in many models of interest, such as those with GUT-scale universality relations among the sparticle masses, the annihilation rate is dominated by sfermion exchange. As one approaches the upper limit on the neutralino mass, the cross section is maximized by taking sfermion masses as small as possible: in this case, the sleptons $\tilde{\ell}$ are nearly degenerate with the neutralino LSP χ [1].

When the LSP is nearly degenerate with the next-to-lightest supersymmetric particle (NLSP), it is known [18] that new important coannihilation channels must be included to determine the relic neutralino density. Thus, in addition to the self-annihilation process $\chi\chi \to$ anything, the effective annihilation cross section includes important contributions from coannihilation processes involving slightly heavier sparticles $\tilde{X}, \tilde{Y}$: $\chi\tilde{X} \to$ anything, $\tilde{X}\tilde{Y} \to$ anything, weighted by the corresponding Boltzmann density suppression factors:

$$\sigma_{eff} \sim \sigma(\chi\chi) + \Sigma_{\tilde{X}} e^{-(m_{\tilde{X}} - m_\chi)/T_f} \sigma(\chi\tilde{X}) + \Sigma_{\tilde{X},\tilde{Y}} e^{-(m_{\tilde{X}} + m_{\tilde{Y}} - 2m_\chi)/T_f} \sigma(\tilde{X}\tilde{Y}) \tag{1}$$

In the parameter region of interest after taking into account the LEP exclusions of light sparticles, the most important coannihilation processes are those involving the NLSP $\tilde{\tau}$ and other sleptons: $\tilde{e}, \tilde{\mu}$, which are all taken into account in the following analysis [14]. Several of these coannihilation cross sections are much larger than that for $\chi\chi$ annihilation close to threshold, because they do not exhibit P-wave suppressions. Therefore, coannihilation is an essential complication.

As noted above, since the resulting LSP relic density $\Omega_\chi h^2$ increases as σ_{eff} decreases, and since σ_{eff} decreases as $m_0, m_{1/2}$ increase, one expects generically that $\Omega_\chi h^2$ should *increase* with *increasing* $m_0, m_{1/2}$. This simple correlation is complicated in the presence of nearby s-channel Z^0 and Higgs poles in the annihilation cross sections, but the LEP exclusions

[1]The GUT universality conditions then imply that the squarks are considerably heavier.

now essentially rule out this possibility [19]. As mentioned earlier in the paper, the preferred range of cold dark matter density is $0.1 \lesssim \Omega_{CDM} h^2 \lesssim 0.3$. It is possible that all the cold dark matter may not consist of LSPs χ, so we can at best assume that $\Omega_\chi h^2 \leq \Omega_{CDM} h^2 \lesssim 0.3$. However, this *upper limit* on $\Omega_\chi h^2$ is sufficient to infer an *upper limit* on $m_0, m_{1/2}$ [2]. In [14], the values of the two key supersymmetry-breaking inputs $m_0, m_{1/2}$ were constrained so that neutralino relic density should fall within the desired range. Roughly speaking, when $m_{1/2} \lesssim 400$ GeV, there is a relatively broad allowed range for m_0 between about 50 and 150 GeV, depending on $\tan\beta, A$ and the sign of μ. For values of $m_{1/2} \gtrsim 400$ GeV, coannihilation becomes important, and m_0 is restricted to a relatively narrow range of typical thickness $\delta m_0 \sim 20$ GeV. The maximum value of $m_{1/2}$ is determined by the point where there is no longer any value of m_0, such that the neutralino mass is less than the $\tilde{\tau}_R$ mass and $\Omega_{CDM} h^2 < 0.3$. This occurs when $m_{1/2} \simeq 1400$ GeV, corresponding to the neutralino mass of about 600 GeV mentioned previously.

This is the essence of our argument that the relic density calculation can be used to specify the e^+e^- collider energy required to produce sparticles.

The upper limit to the neutralino mass including coannihilation effects of $m_\chi \lesssim 600$ GeV is relatively insensitive to such MSSM parameters as $\tan\beta$ and A. As in [14], we consider here the two cases $\tan\beta = 3, 10$, and initially set A close to the weak-CCB value $A = -m_{1/2}$. As mentioned earlier, the upper limit on m_χ implies that the threshold for pair-producing sparticles must be at least $E_{CM} = 1200$ GeV. In fact, when the limit $m_\chi \sim 600$ GeV is reached, one also has $m_\chi = m_{\tilde{\tau}_1}$, where the NLSP $\tilde{\tau}_1$ is the lighter stau mass eigenstate, so the threshold for the reaction $e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$ is also ~ 1200 GeV. Moreover, the mass of the $\tilde{e}_R$ is also not far above 600 GeV, so the threshold for $e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-$ is also not far beyond 1200 GeV. In addition, it is easy to check that even if one allows $m_\chi < m_{\tilde{\tau}_1}$, which is possible if $m_\chi < 600$ GeV, the threshold for $e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$ is never above 1200 GeV. These arguments are all suggestive that $E_{CM} = 1200$ GeV may be sufficient for an e^+e^- linear collider to observe supersymmetry, but any such conclusion must hinge upon the analysis of the observability of the sparticle pair-production cross section that we undertake next.

[2]On the other hand, the *lower bound* on $\Omega_{CDM} h^2 \gtrsim 0.1$ cannot be transferred to a lower bound on Ω_χ, and hence there are *no corresponding lower bounds* on $m_0, m_{1/2}$, except for those imposed by slepton searches and/or the requirement that the $\tilde{\tau}$ not be the LSP.

3 Analysis of Sparticle Pair-Production Cross Sections

In order to determine the region of the $(m_0, m_{1/2})$ plane that can be explored with a linear e^+e^- collider of given E_{CM}, we have calculated the total observable production cross section for the pair production of sparticles $e^+e^- \to \tilde{X}\tilde{Y}$, where $\tilde{X}$ and $\tilde{Y}$ are not necessarily particle and antiparticle [20]. In this context, 'observable' means that we do not include pair production of the LSP: $e^+e^- \to \chi\chi$. Nor do we include sneutrino pair production: $e^+e^- \to \tilde{\nu}\tilde{\bar{\nu}}$, although some $\tilde{\nu}$ decays might be visible. Also, the production cross sections for heavier neutralinos χ', e.g., $e^+e^- \to \chi\chi'$, are corrected for invisible χ' decay branching ratios. Finally, we assume that the ordinary particles emitted in a sparticle decay chain are observable only if the mass difference $\Delta M > 3$ GeV.

We assume an integrated luminosity $\mathcal{L} = 100$ fb^{-1} [1]. In order to estimate the corresponding sensitivity to the new-physics cross section σ, the relevant quantity is $B \equiv \sqrt{\sigma_{bg}}/\epsilon$, where σ_{bg} is the residual cross section for background processes, and ϵ is the signal-detection efficiency. As usual, a five-standard-deviation discovery is likely if $\sigma > 5 \times B/\sqrt{\mathcal{L}}$, whereas, in the absence of any observation, new-physics processes with $\sigma > 2 \times B/\sqrt{\mathcal{L}}$ will be excluded at about the 95 % confidence level. At LEP 2, for mass differences between the produced sparticle and the LSP that are not too small, the background to searches for charginos $\chi^\pm$ and sleptons is mainly due to $W^\pm$ production, and typical values for B were in the range $3 \div 6$ (fb$^{+\frac{1}{2}}$). At the LC we expect cleaner background conditions for both slepton and chargino searches because the $W^\pm$ should be more easily distinguishable, and also $\sigma(e^+e^- \to W^+W^-)$ is smaller. It is therefore likely that B is smaller than at LEP 2. We adopt a conservative approach and scale B roughly by $\sigma(e^+e^- \to W^+W^-)$, taking $B = 2$ (fb$^{+\frac{1}{2}}$), which gives a lower limit on the discoverable cross section of 1 fb, and an exclusion upper limit of 0.4 fb.

Fig. 1 shows the physics discovery reach in the $(m_0, m_{1/2})$ plane for $\tan\beta = 3, 10$ provided by the processes $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$, neutralinos and charginos $\chi^+\chi^-$ for collisions at e^+e^- collisions at $E_{CM} = 500, 1000, 1250, 1500$ GeV, compared with the allowed cold dark matter region (shaded). The solid lines in Fig. 1 correspond to the estimated discovery cross section of 1 fb for $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$, and the broken lines to the kinematic limit $m_{\chi^\pm} = E_{CM}/2$. We see no big differences between the plots for the different signs of μ, nor indeed for the different values of $\tan\beta$. We note that $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$ (solid lines) provides the greatest reach for each of the values $E_{CM} = 500, 1000, 1250, 1500$ GeV studied, and that chargino pair production $e^+e^- \to \chi^+\chi^-$ (broken lines) becomes progressively less important as E_{CM} increases.

We see in Fig. 1 the extent to which the region favoured by the cosmological requirement

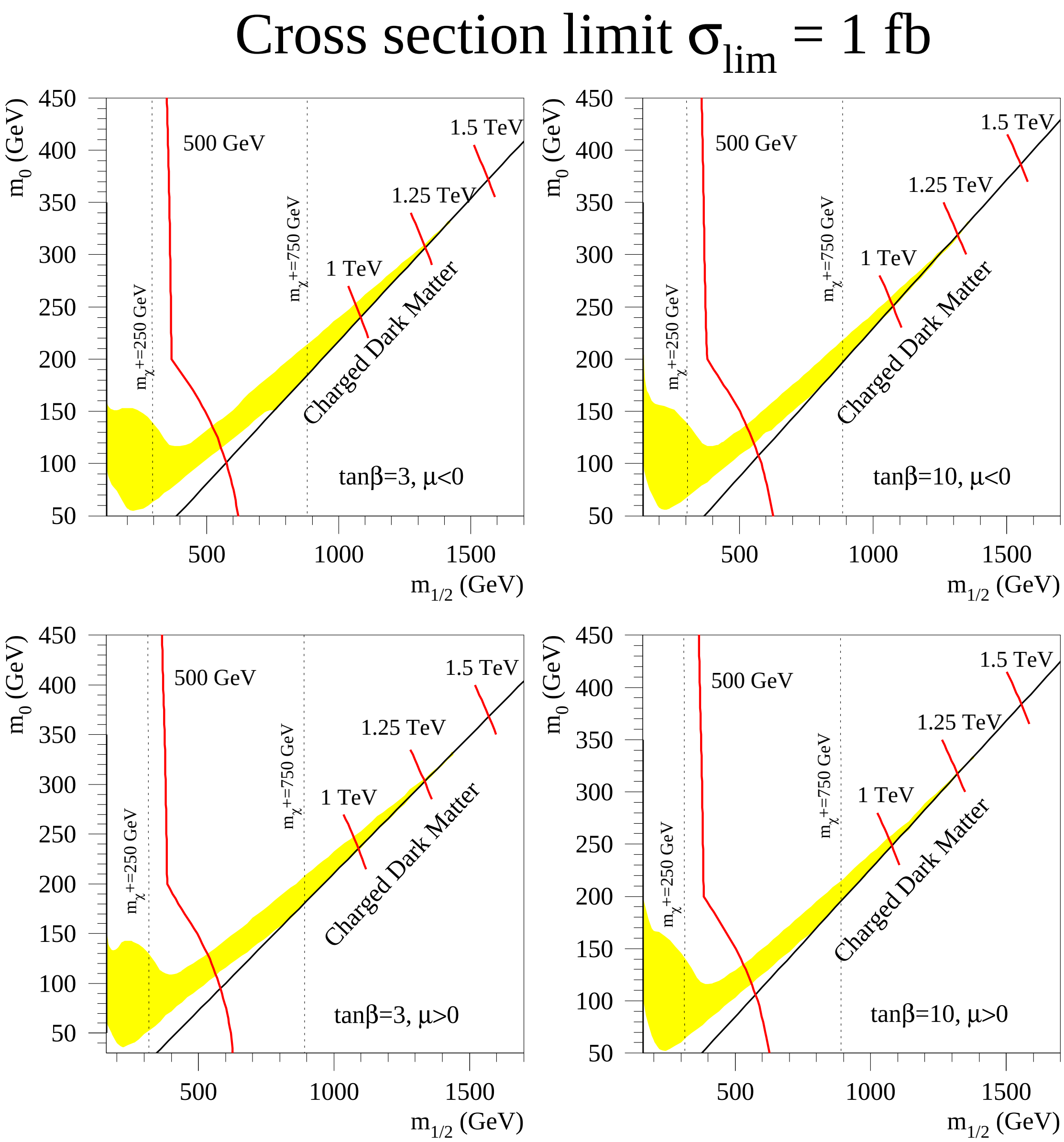

Figure 1: *Discovery sensitivity in the* $(m_0, m_{1/2})$ *plane for* $\tan\beta = 3$ *(left panels) and* 10 *(right panels) provided by searches for* $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$ *and neutralinos (solid lines) and* $\chi^+\chi^-$ *(broken lines) for collisions at* $E_{CM} = 500, 1000, 1250, 1500$ *GeV. The allowed cold dark matter regions are shaded. The top (bottom) panels are for* $\mu < (>) 0$*, and the value* $A = -m_{1/2}$ *is used.*

that $0.1 \leq \Omega_\chi h^2 \leq 0.3$ may be covered by LC searches at different energies. In particular, about a half of this region is covered by sparticle searches at $E_{CM} = 500$ GeV, a somewhat larger fraction (but not all) is covered at $E_{CM} = 1000$ GeV, and full coverage of the favoured region is approached only when $E_{CM} = 1500$ GeV [3]. The reason why more than 1200 GeV is required is the P-wave threshold suppression for the observable processes with the lowest thresholds near the point of the cosmological region, namely the reactions $e^+e^- \to \tilde{\ell}^+_R \tilde{\ell}^-_R$.

Fig. 2 shows as three-dimensional 'mountains' the full observable sparticle cross section for $\tan\beta = 10$ and $\mu > 0$ for $E_{CM} = 500, 1000, 1250$ and 1500 GeV, including also other pair-production processes. The irregularities in the outline of the three-dimensional 'mountain' plot correspond to the opening up of different sparticle pair-production thresholds. We see again that $E_{CM} = 500$ GeV is not adequate to cover much of the cosmological region, that $E_{CM} = 1000$ GeV does not cover a significant fraction of the high-$m_{1/2}$ tail opened up by coannihilation, and that $E_{CM} \geq 1500$ GeV covers the cosmological region. We find similar features for $\tan\beta = 10$ and $\mu < 0$, and also for $\tan\beta = 3$ and both signs of μ (not shown).

We now return to the tip of the cosmological tail, which occurs when $m_\chi \sim 630(610)$ GeV for $\tan\beta = 3(10)$ for our default option $\Omega_\chi h^2 \leq 0.3$, and explore in more detail how much E_{CM} beyond 1200 GeV is required to be sure of detecting supersymmetry. Fig. 3 shows the contributions to the effective observable cross section from the dominant reactions $e^+e^- \to \tilde{\ell}^+_{L,R}\tilde{\ell}^-_{L,R}$. Close to threshold, only pair production of the $\tilde{\ell}_R$ states is accessible, which exhibits a P-wave suppression. The associated-production process $e^+e^- \to \tilde{e}_L\tilde{e}_R$ kicks in at somewhat higher energies, and rapidly dominates, because of its S-wave threshold. This is the origin of the kink seen in the rise of the total cross section in each of the panels of Fig. 3, where the discovery and exclusion sensitivities are also shown as horizontal broken lines. We see that E_{CM} only just above $2m_\chi \sim 1200$ GeV is not sufficient for sparticle discovery, because of the small observable cross section. We recall that, for our assumed integrated luminosity of 100 fb^{-1} and detector performances, the discovery cross-section limit would be 1 fb, as indicated by the upper horizontal broken line in Fig. 3. Of course, this may be altered by different assumptions on the integrated luminosity and/or detection efficiency [4].

Each of the panels in Fig. 3 exhibits alternative curves to be compared with our default choices $\Omega_\chi h^2 = 0.3$ and $A = 0$. The curves for $\Omega_\chi h^2 = 0.4$ are for instruction only. In this case, one finds $m_\chi \lesssim 740(710)$ GeV for $\tan\beta = 3(10)$, but it is very difficult to reconcile such a large value of $\Omega_\chi h^2$ with the emerging measurements of cosmological parameters [5]. In fact,

[3] We note in passing that a LC with $E_{CM} = 500$ GeV would have seemed perfectly adequate if coannihilation were not taken into account.

[4] We note, in particular, that higher luminosities may be achievable at higher E_{CM}.

[5] For the record, for $\Omega_\chi h^2 < 0.5$, the upper limit on the neutralino mass increases to $m_\chi \lesssim 830(800)$ GeV

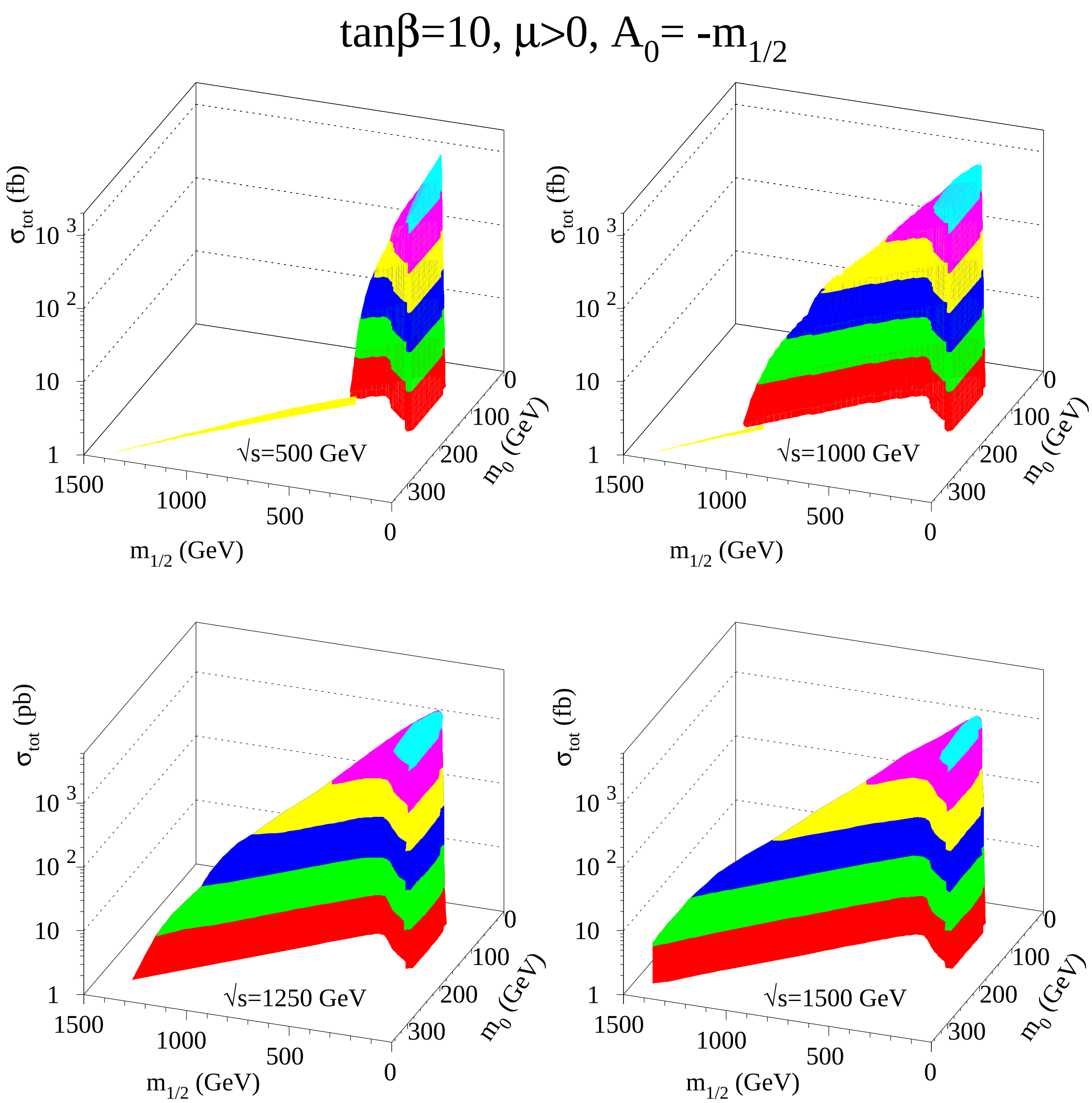

Figure 2: *The observable sparticle pair-production cross section in the* $(m_{1/2}, m_0)$ *plane for* $\tan\beta = 10$, $\mu > 0$ *and* $A = -m_{1/2}$, *for* $E_{CM} = 500, 1000, 1250$ *and* 1500 *GeV. Note that the vertical scale is logarithmic, and that cross-section contours are indicated by changes in the shading of the cross-section 'mountain'. The cosmologically-preferred domain of* $(m_{1/2}, m_0)$ *is visible in projection in the top two panels: in the bottom two panels, it is obscured by the 'mountain'.*

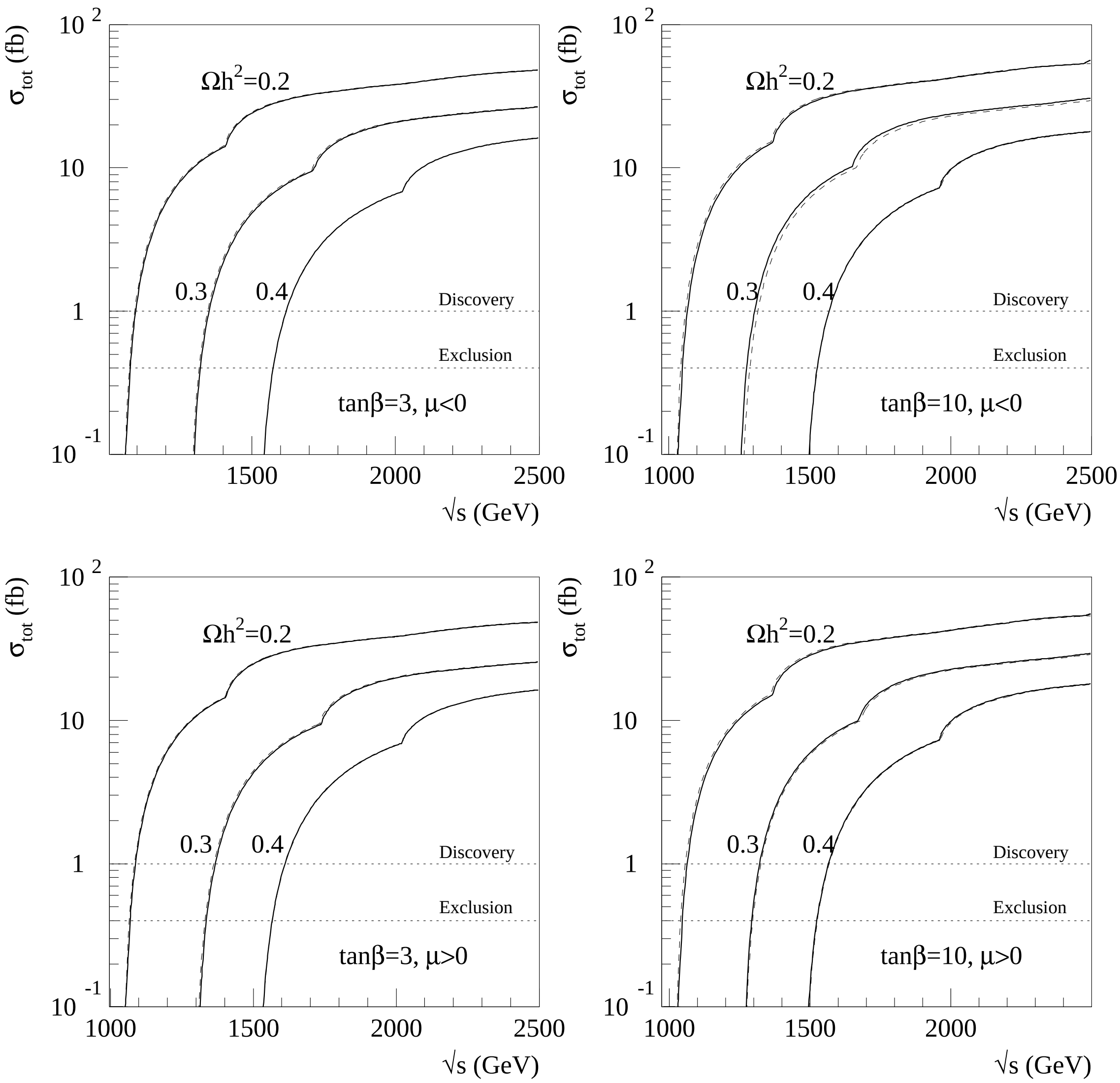

Figure 3: *The total observable cross section for* $e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-$ *processes, as a function of* E_{CM}*, for the points at the tips of the region of* $m_{1/2}, m_0$ *allowed for* $\Omega_\chi h^2 \leq 0.2, 0.3$ *(our preferred choice) and 0.4, with the usual choices* $\tan\beta = 3, 10$ *and both signs of* μ*. The solid lines are for* $A = -m_{1/2}$*, and the dashed lines for* $A = 0$*. The horizontal broken lines are our estimates of the possible discovery and exclusion cross sections.*

we actually believe that allowing $\Omega_\chi h^2 \leq 0.3$ is already quite conservative. For the preferred observational value $h \sim 1/\sqrt{2}$, this would correspond to $\Omega_\chi \leq 0.6$, which extends far beyond the currently favoured range $\Omega_\chi \leq 0.4$. If instead one enforces $\Omega_\chi h^2 \leq 0.2$, one finds that the maximum value of the LSP mass becomes $m_\chi \sim 520(500)$ GeV, for $\tan\beta = 3(10)$ and $E_{CM} = 1500$ TeV would be adequate, as seen in Fig. 3. Indeed, in this case, $E_{CM} = 1200$ GeV would be sufficient to cover all the region of the $(m_0, m_{1/2})$ favoured by cosmology. We also show in Fig. 3 comparisons between the cross sections at the extreme points for $A = 0$ and $-m_{1/2}$. Our conclusions are clearly insensitive to the ambiguity in the choice of A.

4 Conclusions

Finally, we show in Fig. 4 the fraction of the cosmologically-allowed region of the $(m_{1/2}, m_0)$ plane that can be explored by a LC as a function of the accessible limiting cross section σ_{lim}, for different values of E_{CM}. When the detector perfomances are specified, the values of σ_{lim} correspond to different values of the available luminosity, as indicated. We see in Fig. 4 that a LC with $E_{CM} = 1.5$ TeV would cover all the cosmological region if $\sigma_{lim} \lesssim 5$ fb [6], and one with $E_{CM} = 1.25$ TeV if $\sigma_{lim} \lesssim 0.5$ fb. On the other hand, a LC with $E_{CM} = 1$ TeV could never cover all the cosmological region, and a LC with $E_{CM} = 0.5$ TeV covers ~ 60 % of it [7].

The conclusions to be drawn from this analysis are somewhat subjective, since they depend how much you are prepared to bet at what odds. It could well be that new cosmological data might inform better your choice. For example, you could become more sanguine about the prospects for a lower-energy LC if the upper limit on $\Omega_\chi h^2$ could be decreased to 0.2. Our point in this paper has been to establish that there is a phenomenological connection between the LC energy and supersymmetric dark matter, and we believe that Fig. 4 summarizes the best advice we can offer at the beginning of the third millennium.

Acknowledgments

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for $\tan\beta = 3(10)$.

[6] A LC with $E_{CM} = 2$ TeV would always cover all the cosmological region, even for a very pessimistic assumption on σ_{lim}.

[7] Fig. 4 is plotted using a linear measure for the cosmological region. The prospects for lower-energy machines would seem brighter if one used a logarithmic measure of the parameter space, e.g., using this measure, a LC with $E_{CM} = 0.5$ TeV would cover over 80 % of the cosmological region.

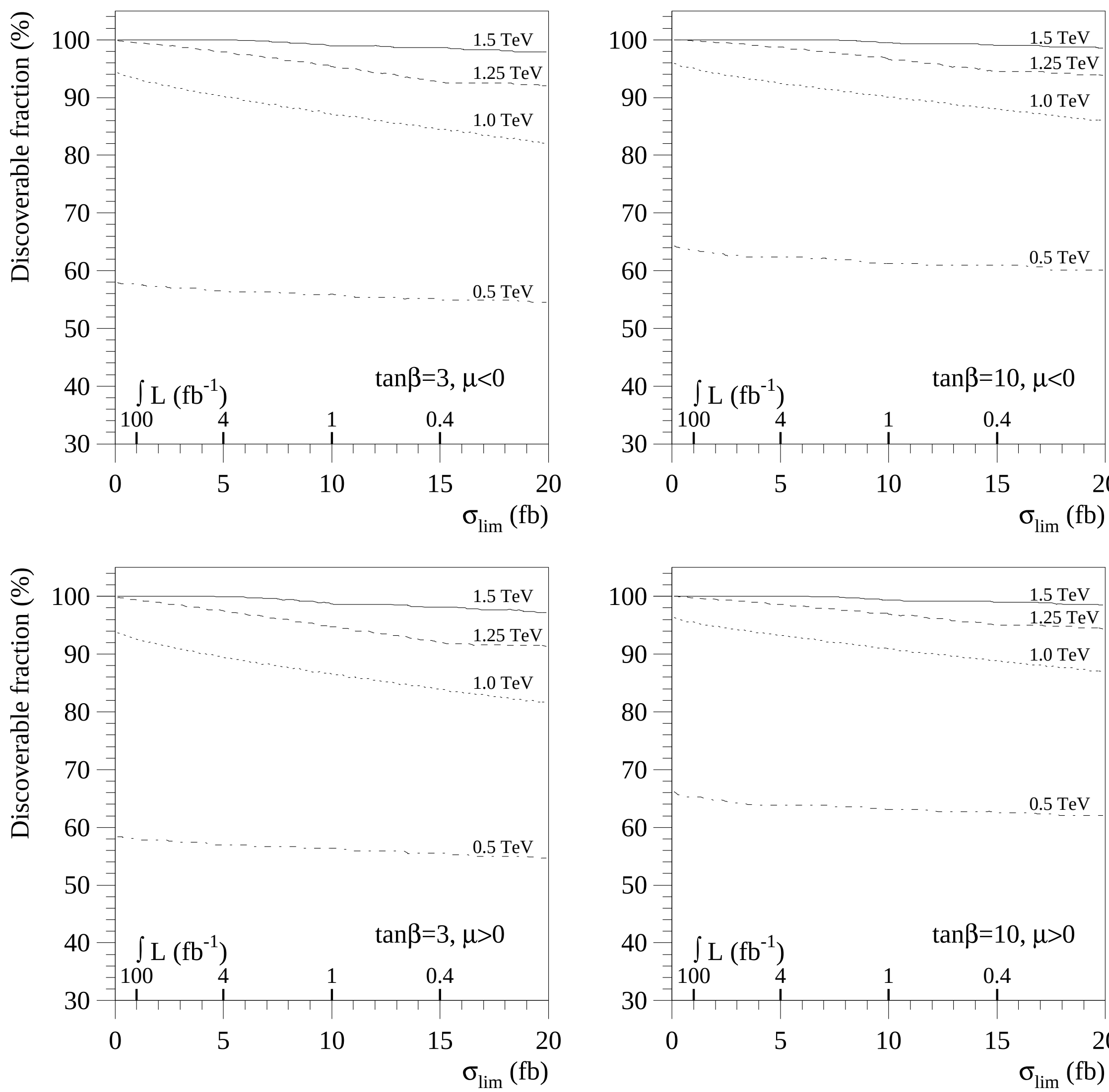

Figure 4: *The discoverable fractions of the region of the* $(m_{1/2}, m_0)$ *plane allowed by cosmology for* $0.1 \leq \Omega_\chi h^2 \leq 0.3$ *that is accessible to a LC as a function of accessible cross section* σ_{lim}*, for different values of* E_{CM}*, for each of our scenarios* $\tan\beta = 3, 10$ *and both signs of* μ*, assuming* $A = -m_{1/2}$*. Also indicated is the correspondence between luminosity and* σ_{lim} *for the detector performances assumed in this paper.*

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